Project ID# eems020
Pillar(s): CAVs

U.S. DEPARTMENT OF ENERGY
SMARTMOBILITY
Systems and Modeling for Accelerated Research in Transportation

Multi-Scenario Assessment of Optimization Opportunities due to Connectivity and Automation

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2019 Vehicle Technologies Office Annual Merit Review
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Argonne NATIONAL LABORATORY
INL Idaho National Laboratory
BERKELEY LAB
OAK RIDGE National Laboratory
NREL NATIONAL RENEWABLE ENERGY LABORATORY

Overview

Timeline

- Project start: October 1, 2016
- Project end: September 30, 2019
- Percent complete: 65%

Budget

- Total project funding
  - $1.077M
  - DOE share: 100%
  - Contractor share: 0%
- Funding for FY 2019
  - $381K

Barriers

- Availability of integrated tools, **techniques**, & core capabilities to understand & **identify** the most important levers to improve the energy productivity of future integrated mobility systems
- Accurate assessment of transportation system-wide energy impacts of optimal coordination of connected and automated vehicles

Partners

- Lead: ORNL
- DOE SMART Mobility Lab Consortium
- Argonne National Laboratory➔ Vehicle models
- University of Delaware➔ Human-in-the-loop, small scale experimental data
- Active discussion with AT&T

Relevance

- **Challenges**
  - Much research in connectivity and automation is focused on safety only
  - High uncertainty about energy impacts
  - Further exploration of mobility gains & energy savings potential is needed
- **Objective:**
  - Explore optimization opportunities to increase energy efficiency in full and partial CAV market penetration under diverse traffic scenarios;
  - Develop simulation framework to assess and verify effectiveness
  - Inform public and private sector decision-making in deploying/adopting optimal CAVs control strategies for increased mobility energy efficiency

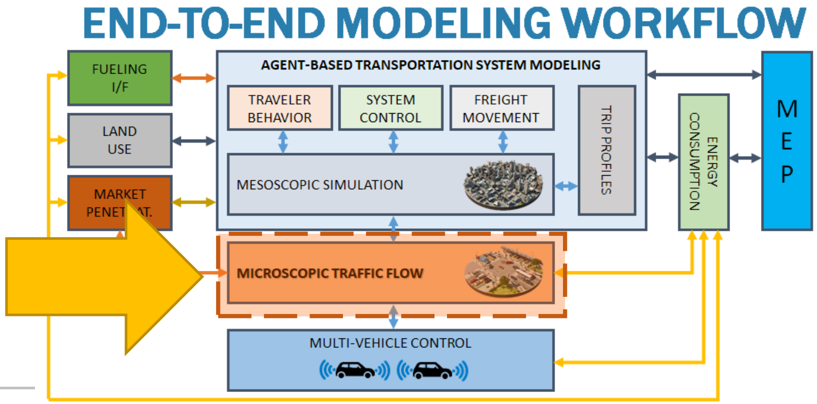
Source: https://jooinn.com/traffic-4.html

Source: https://www.skyscrapercity.com/

Source:https://queuingtheory.wordpress.com/2012/05/02/application-part-3-11/

Relevance

- **Impacts:**
  - Contributing to the SMART Mobility program goal of yielding meaningful insights on how SMART technologies can improve Mobility Energy Productivity
    - Insights regarding efficient coordination/control strategies that could offer energy and mobility improvements
  - Generating a methodology to quantify the benefits of partial market penetrations of optimally coordinated CAVs to inform public and private sector decision-making in deploying optimal vehicle coordination strategies to maximize mobility energy efficiency

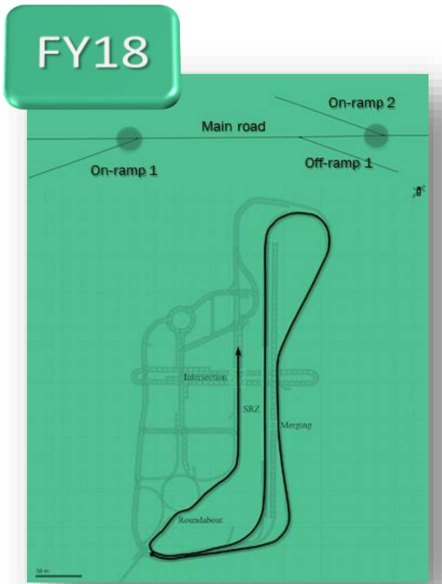


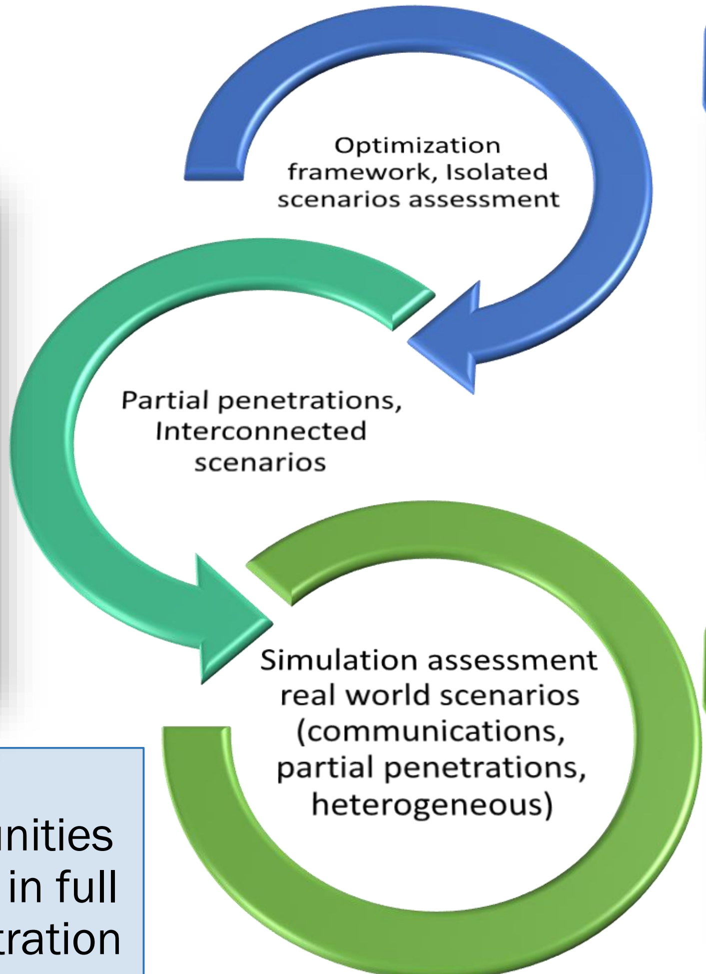
Milestones

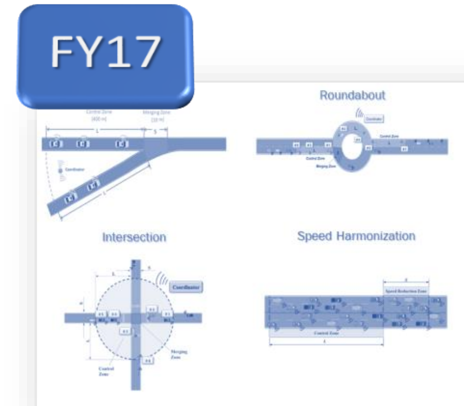
Task	FY18 Q3	FY18 Q4	FY19 Q1	FY19 Q2	FY19 Q3	FY19 Q4
1. Optimal coordination framework adapted to a highway corridor						
2. Impacts quantification highway corridor, heterogeneous traffic						
3. Paper reporting findings						
1. Calibration of baseline scenario using real-world data						
2. Description of strategic lane change control for multilane scenarios						
3. Simulation-based assessment of communication-related instabilities on the merging control system considering a real-world scenario						
4. Summary report						

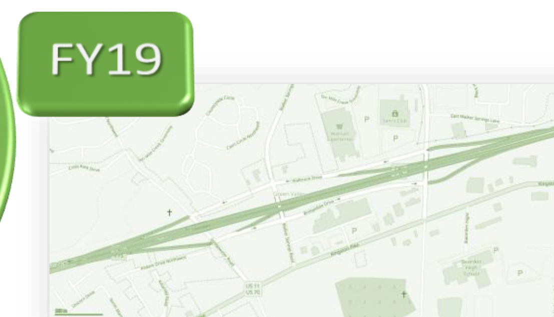
Any proposed future work is subject to change based on funding levels

Approach





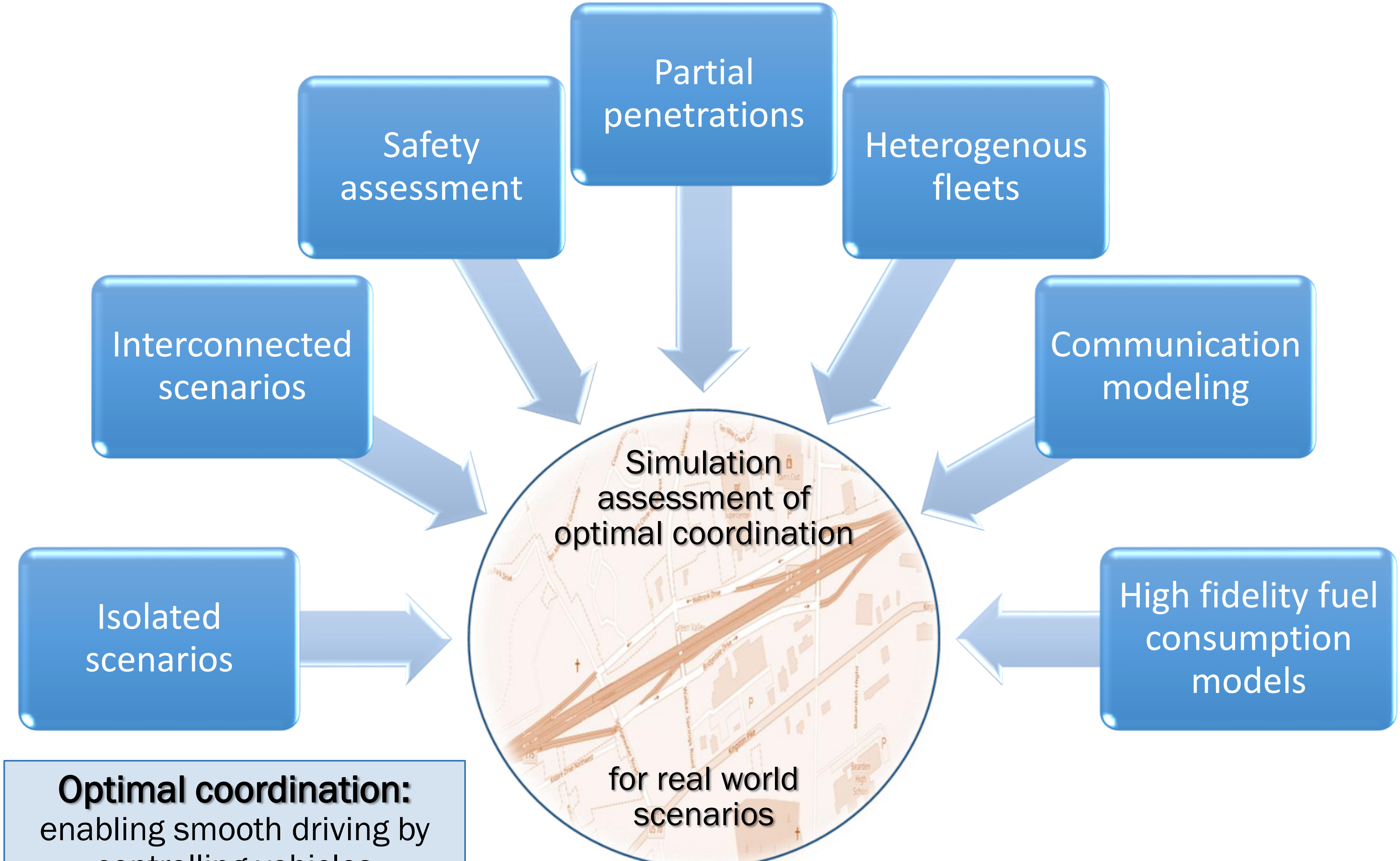




Goal

Explore optimization opportunities to increase energy efficiency in full and partial CAV market penetration under diverse scenarios

Approach



Optimal coordination:
enabling smooth driving by controlling vehicles maneuvers at conflict zones

Technical Accomplishments

Technical Accomplishments and Progress -Summary

1. Safety-oriented analysis of CAVs on-ramp (slide 10)

2. Adaptation of optimal coordination of CAVs to interconnected scenarios
   - Urban corridor (slide 11)
   - Highway corridor (Technical back-up slides)

3. Preliminary partial CAV penetration analysis considering heterogeneous traffic (slides 12, 13)

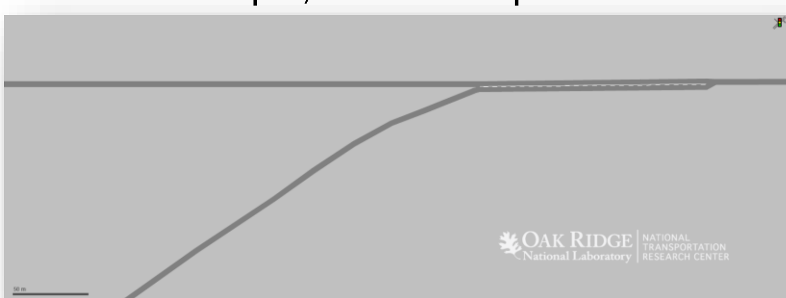
4. Ongoing:
   - Use of high fidelity fuel consumption models (Slide 14)
   - Integration of communication instabilities on the simulation network
     - Package drop and delay modeled as a function of communication distance (Slide 15, 16)
   - Calibration of baseline traffic scenario (Technical back-up slides)

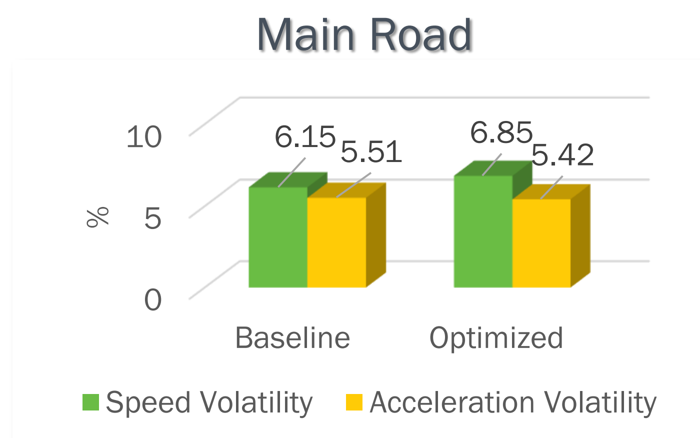
Optimal coordination improves safety by reducing the levels of volatility on the road

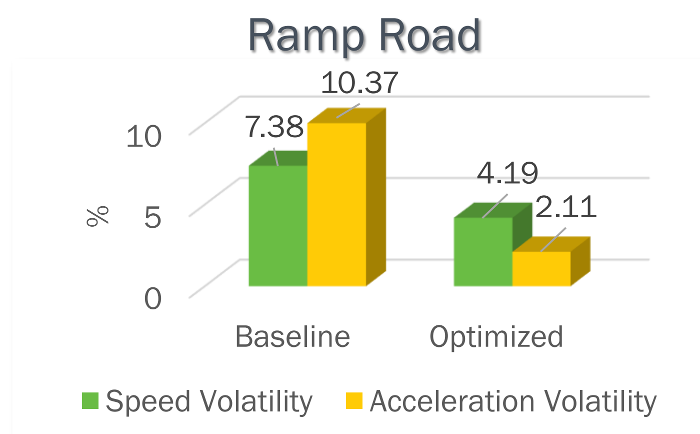
Driving volatility*

- – Percentage of time the acceleration is higher than the mean acceleration plus one or two standard deviations of a data sample
- – Surrogate safety measure

- – Main road demand: 1200 veh/h, Ramp road demand: 800 veh/h
- – Speed limit 40 mph, full CAVs penetration







Optimal coordination of CAVs allows significant **reduction of driving volatility (~43% - 77%)** on the ramp road, at the expense of a small increment of speed volatility on the main road

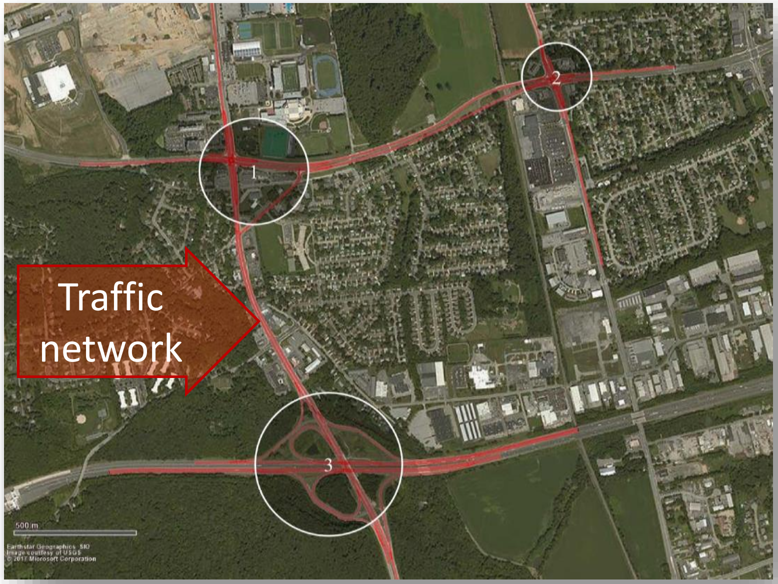
*Wang, X., Khattak, A.J., Liu, J., Masghati-Amoli, G., Son, S., 2014. What is the level of volatility in instantaneous driving decisions? Transp. Res. Part C Emerg. Technol. 58, 413–427. doi:10.1016/j.trc.2014.12.014

Rios-Torres, J., Han, J., Arvin, R., Khattak, A., "Safety, traffic and energy impacts of optimal coordination control systems for connected vehicles at highway on-ramps," (In preparation)

Optimal coordination on interconnected scenarios – Urban corridor

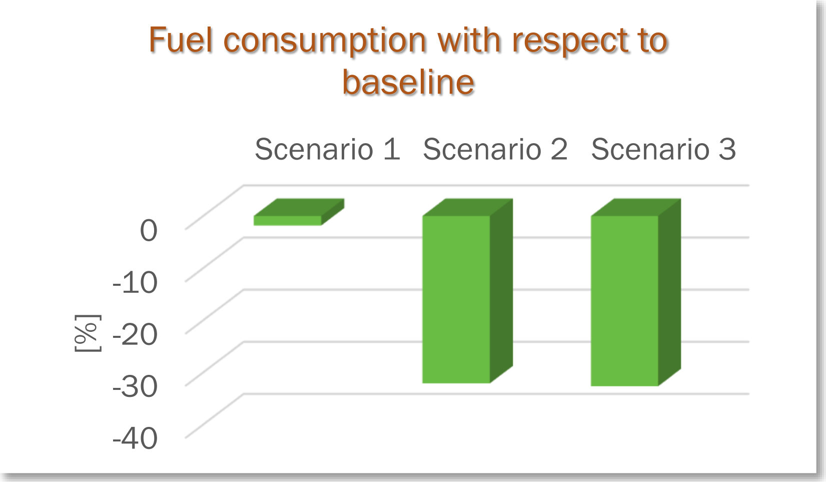
Simulation set-up

Scenario	Vehicle type	Headway (s)	Control zone length (m)	Signal controller
Baseline	Human-driven	1.2	-	Fixed time
1	Uncoordinated AV	0.9	-	Fixed time
2	Coordinated CAV	1.2	150	Disabled
3	Coordinated CAV	0.9	150	Disabled



Highlighted results

- Homogeneous traffic (LDV),
- Full CAVs penetration



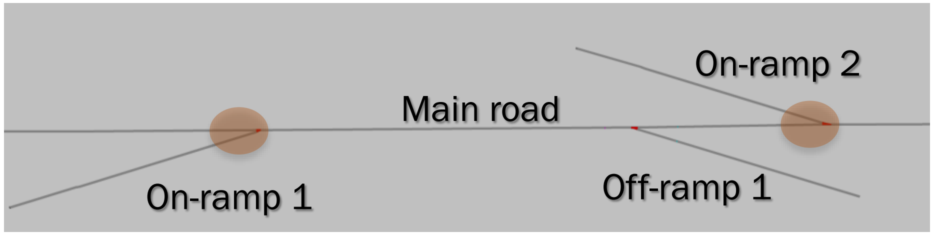
CAVs coordination enables smoother speed patterns with significant fuel consumption reduction compared to uncoordinated CAVs

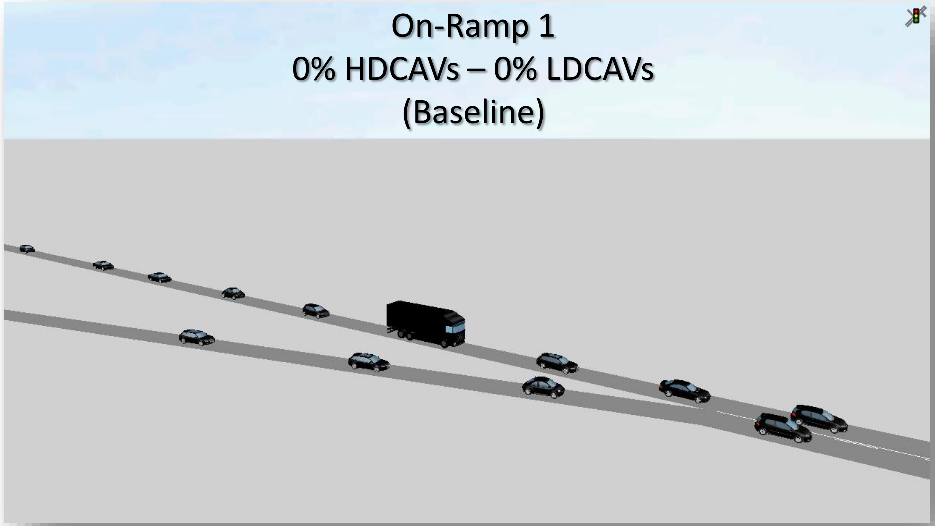
Zhao, L., Malikopoulos, A. A., Rios-Torres, J., "On the Traffic Impacts of Optimally Controlled Connected and Automated Vehicles", Proceedings of the 2019 IEEE Conference on Control Technology and Applications (CCTA) , 2019 (Forthcoming)

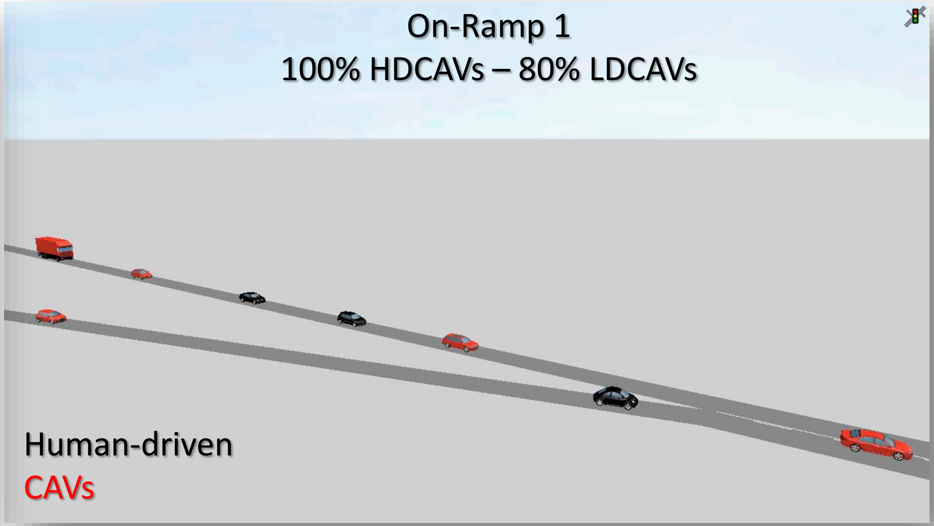
Analysis of partial penetration of optimally coordinated CAVs for interconnected scenarios

- Heterogeneous traffic (LDV + HDV)
- Preliminary analysis for automated heavy duty vehicles interacting with human-driven + CAVs light duty vehicles

Congestion in baseline is mitigated when 100% of the HDVs and 80% of the LDVs are CAVs



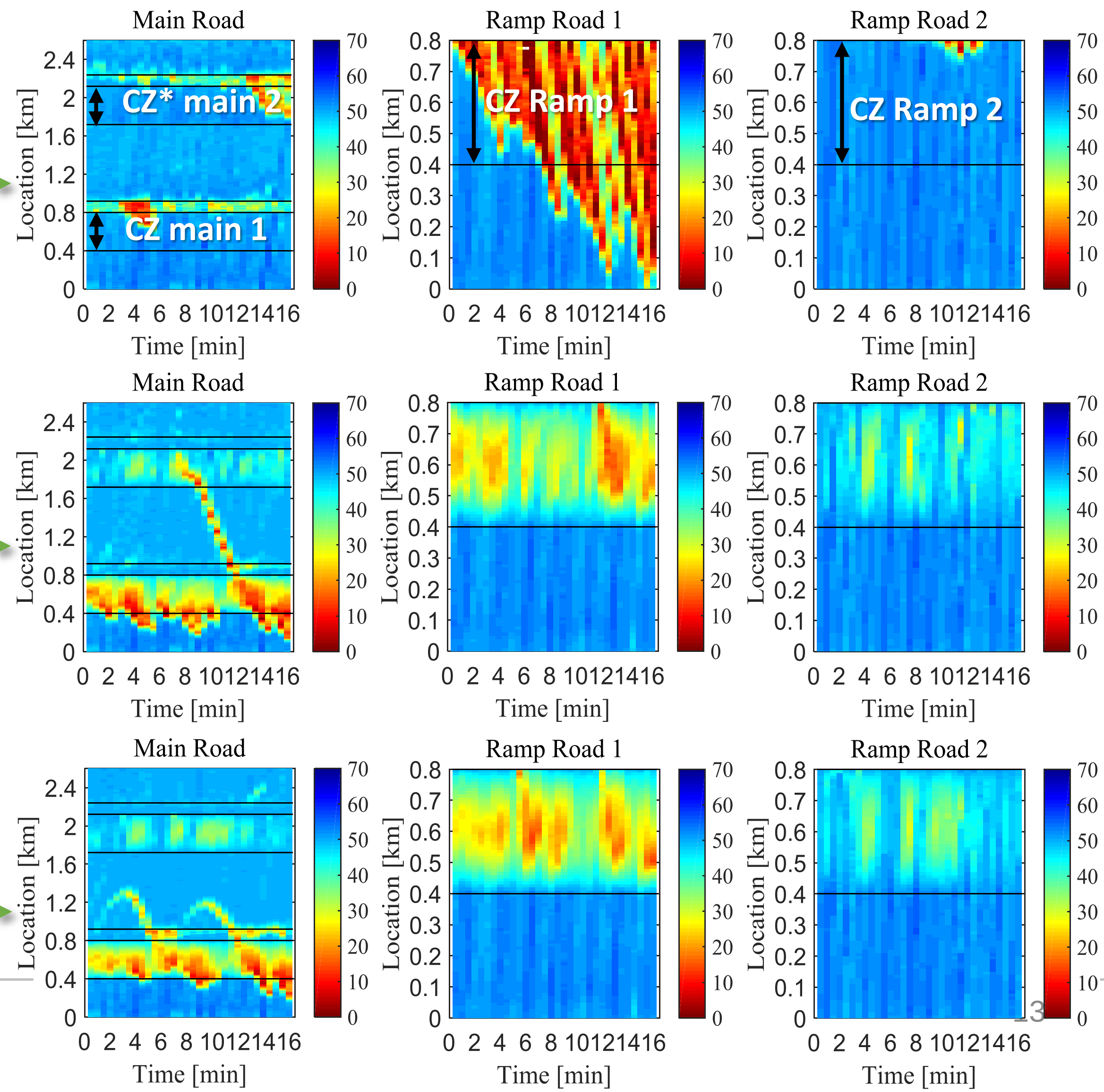




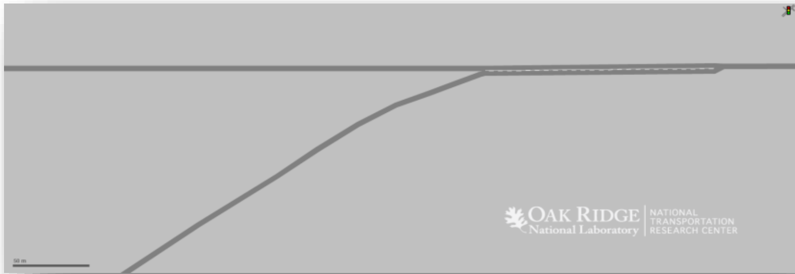
Optimal coordination helps mitigating the slowdown on Ramp Road 1

- **Scenario 1:**
  - 0% PR HDCAVs, 0% PR LDCAVs
  - Heavy traffic on ramp road 1
- **Scenario 2:**
  - 100% PR HDCAVs, 60% PR LDCAVs
  - Ramp road 1 congestion mitigated
  - Some congestion on main road
  - Speed slightly reduced on ramp road 2
- **Scenario 3:**
  - 100% PR HDCAVs, 80% PR LDCAVs
  - Main road congestion slightly improved

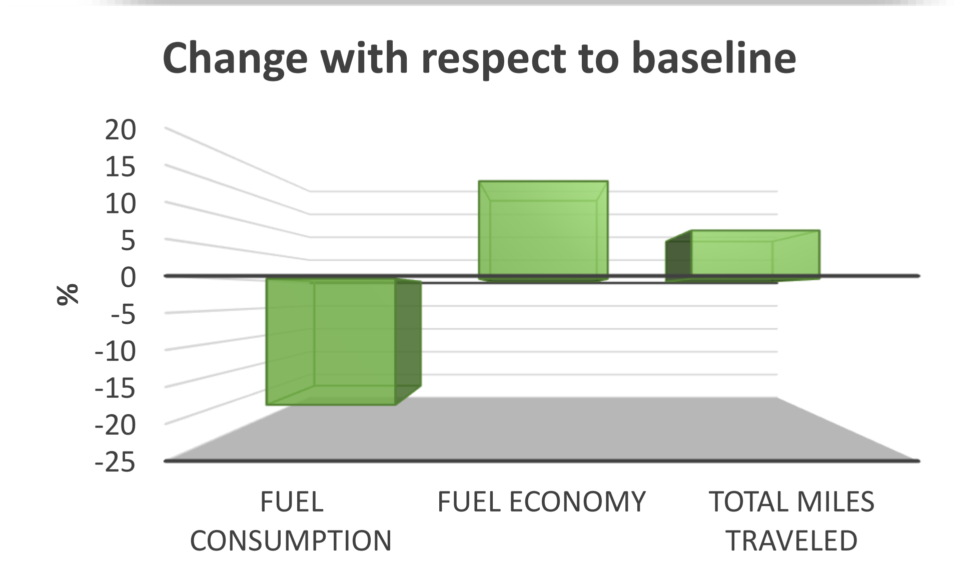
*CZ➔ Control zone

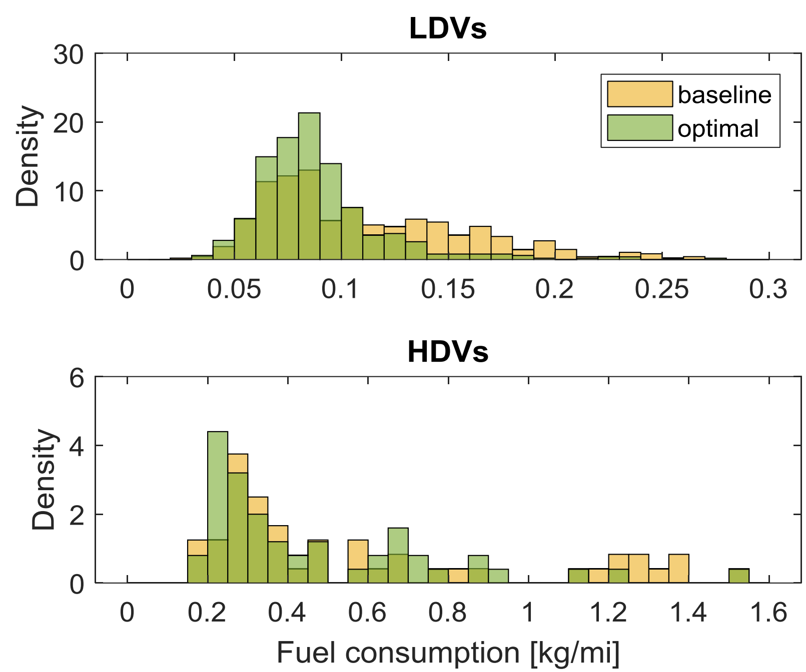


Ongoing: Comprehensive efficiency and emissions analysis with high fidelity models



Optimal coordination delivers significant fuel savings (**about 20%**) in a moderate congested scenario considering current fleet distributions





Ongoing work explores different fleets distribution for different automation levels scenarios (short and long term scenarios)

Ongoing: Laying down the basics for simulation of V2X communications

- Vissim traffic microsimulation network: based on I-40 network (westbound)
  - Current simulation: 378 exit
  - Simulating package drop and delays
  - Delays modeled as a function of the distance
  - Control implemented with external driver model (using MATLAB)

Simulating package drop

- Vissim traffic microsimulation network: based on I-40 network (westbound)
  - Left: pink vehicles have perfect communication
  - Right: pink vehicles are experiencing package drop

Perfect Communication

Package Drop

Responses to Previous Years Reviewers Comments (1)

- **The reviewer noted that many elements of the work are good. The reviewer commented that, as shown on Slide 10, the simplification of fuel used to a surface should really help get to reasonable estimates much quicker than attaching an optimizer to Autonomie. Its drawback is that it is not able to get to the change in improvements due to various vehicle types and technologies.**

- **Actions taken:**

- For the coming simulation assessment work, we are using higher fidelity vehicle models that have been provided by the ANL team
- The models consider heterogeneous fleets and different distributions of vehicle makes and models according to predefined scenarios in the current, short and long term
- Some assumptions are included regarding the energy consumption due to sensors and computation

Responses to Previous Years Reviewers Comments (2)

- **The reviewer stated that fuel comparison estimates need to include the added accessory loads for CAV. The reviewer noted that the lack of this is overstating the benefit. The reviewer expressed interest in seeing the stated improvements based on a more comprehensive driving pattern, and opined that, suggesting a 60% fuel saving for an on-ramp maneuver is overstating the true effectiveness of CAV technology.**

- **Actions taken:**

- For the coming and recent simulation assessment work, we are using different higher fidelity vehicle models that have been provided by the ANL team. Such models include some estimates for the added accessory loads for CAV
- Ongoing efforts are focusing on combining the different pieces to allow assessment of the coordination framework using simulation scenarios based on traffic data from real world corridors

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

- **SMART Mobility Consortia:**

Vehicle models

Traffic analysis

HIL Validation

- **Collaborations:**

Subcontractor, human-in-the-loop, small scale experimental data for validation

Non-funded collaboration – safety

REMAINING CHALLENGES AND BARRIERS

- **Control problem formulation**
  - Adaptation to different powertrain types is needed and require higher fidelity models
- **Calibration**
  - Real traffic data is limited
- **Simulation**
  - Comprehensive simulation assessment is computationally and time intensive
- **Diversity in actual traffic scenarios**
  - Need to represent agents diversity (powertrain types, driver diversity, etc)

PROPOSED FUTURE RESEARCH

– How to adapt the optimal coordination control to ensure vehicles with different time response can follow the control input ?

– Integration of the different assessment measures and scenarios into a single framework

Any proposed future work is subject to change based on funding levels

SUMMARY SLIDE

- **Approach:**
  - Apply optimal control to develop optimal CAVs coordination algorithms adaptable to multiple traffic scenarios.
  - Generate a methodology to assess the benefits to inform public and private sector decision-making in deploying optimal vehicle coordination strategies to maximize mobility efficiency

- **Technical Accomplishments:**
  - Demonstrated the effectiveness of the controller to improve fuel economy and reduce travel time on traffic corridors under 100% penetration of CAVs considering different traffic conditions
  - Preliminary results reveal that 60% penetration of CAVs can aid to mitigate the propagation of traffic bottlenecks at the expense of a slight speed reduction on the main road considering a hypothetical highway corridor with two on-ramps

- **Future Work:**
  - Exploring impacts of optimal coordination applied to simulated traffic scenarios based on real-traffic data and the effects of communication instabilities in the overall performance of the control

Any proposed future work is subject to change based on funding levels

QUESTIONS?

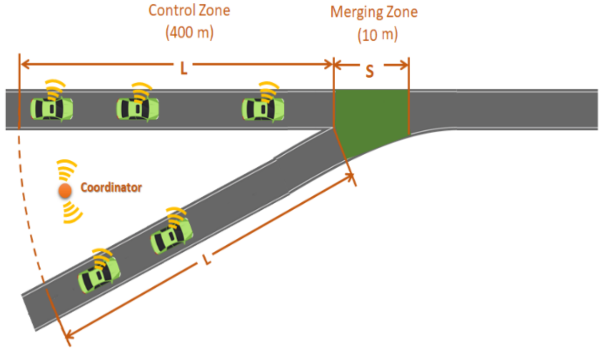
TECHNICAL BACK-UP SLIDES

CAVs Optimal Coordination Framework reduces energy by minimizing vehicles' acceleration

Optimal control problem

$$\min_{u_i} J = \min_{u_i} \frac{1}{2} \sum_{i=1}^{n} \int_{t_i^o}^{t_i^f} u_i^2 dt$$

We aim to minimize the vehicles' acceleration in the control zone and coordinate their access to the merging zone to avoid conflicts



Subject to:

Vehicle dynamics

$$\dot{p}_i(t) = v_i(t)$$
$$\dot{v}_i(t) = u_i(t),$$

Boundary conditions

$$\dot{p}_i(t_i^0) = 0, \quad \dot{p}_i(t_i^f) \text{ given}$$
$$\dot{v}_i(t_i^0) \text{ given}, \ \dot{v}_i(t_i^f) \text{ given}$$

Safety Constraint

$$u_i \in R_i, \qquad R_i \triangleq \{u_i(t) \in [u_{\min}, u_{\max}] \mid p_i(t) \le p_k(t) - \delta,$$
$$v_i(\mathrm{t}) \in [v_{\min}, v_{\max}], \forall i \in \mathcal{N}(t), |\mathcal{N}(t)| > 1, \forall t \in [t_i^0, t_i^f]\},$$

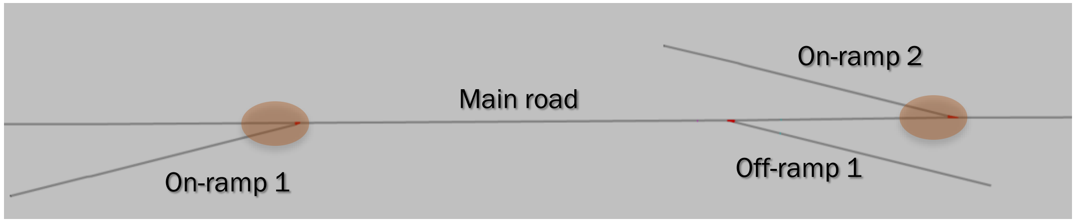
Where R_i *is the control interval,* δ *a safe headway distance and* **k** *the leader of vehicle* ***i****.*

Analytical solution is found through application of Hamiltonian analysis

* ***J. Rios-Torres*** and A. A. Malikopoulos, "Automated and Cooperative Vehicle Merging at Highway On-Ramps," in IEEE Transactions on Intelligent Transportation Systems, vol. 18, no. 4, pp. 780-789, April 2017. doi: 10.1109/TITS.2016.2587582

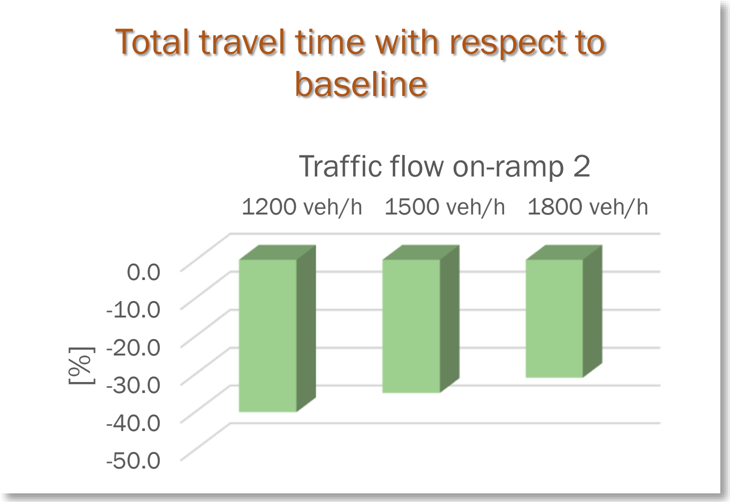
Optimal coordination on interconnected traffic scenarios – Highway corridor

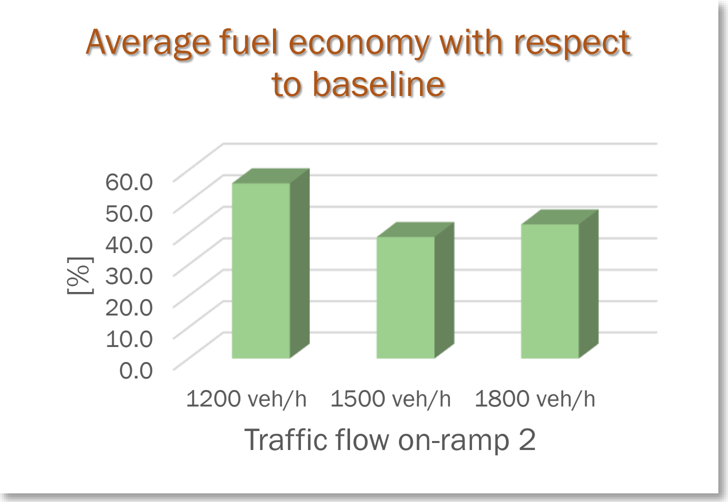
- Fuel economy and travel time are improved when all the vehicles are coordinated
- At higher traffic flows on the on-ramp 2 the benefits are attenuated



Simulation set-up

- Homogeneous traffic
- Traffic flow:
  - Main: 1400 veh/h
  - Ramp 1: 600 veh/h
  - Ramp 2:
    - 1200 veh/h
    - 1500 veh/h
    - 1800 veh/h
- Exit rate at off ramp: 30%





Calibration of baseline scenario

- Data from Tennessee Department of Transportation's (TDOT) traffic sensors and cameras
  – I-75 near Cleveland, TN, markers 19 to 27,
- Genetic algorithm for calibration